IV. SPECTRAL LINE PRIORITIES FOR RADIO ASTRONOMY

The International Astronomical Union (IAU) has a special working group dedicated to a periodic review and update of the list of spectral lines of greatest interest to astronomers. The list is updated every three years. The CORF has followed the IAU list for the most part in creating Tables 4 and 5, which list Priority 1 and Priority 2 spectral lines, respectively. (Lines of interest for remote sensing and atmospheric research are discussed in Table 1.)

In general, the committee believes that Priority 1 lines merit unshared, passive exclusive allocations. These are lines that give us information about important and widespread astrophysical phenomena, including astrochemical reactions. Priority 2 lines are often not so well understood or studied but because of their potential for wider study deserve at least footnote protection.

TABLE 4 Priority 1 Spectral Lines

Spectral Line Frequencies	Atomic and Molecular Species
1420.406 MHz	Hydrogen [The allocation 1330-1427 MHz is needed to permit observations of hydrogen in our galaxy and other nearby galaxies with radial velocities up to 20,000 km/s.]
1612.231, 1665.402, 1667.359, and 1720.530 MHz	OH (hydroxyl radical)
4829.660 MHz	H_2CO (formaldehyde)
12.178 GHz	Methanol
22.235 GHz	H_2O (water vapor)
23.694, 23.723, and 23.870 GHz	NH_3 (ammonia)
48.991 GHz	CS (carbon sulphide)
86-92 GHz	Numerous lines, including HCN (hydrogen cyanide) and its ^{13}C, ^{17}O, and ^{18}O isotopes; HNCO (isocyanic acid); formylium HCO^+; HNC (hydrogen isocyanide); and SiO (silicon monoxide)
97.981 GHz	CS (carbon sulphide)
109.782, 110.201, 112.359, and 115.271 GHz	CO (carbon monoxide, including ^{13}C, ^{17}O, and ^{18}O isotopes)
113.14-113.51 GHz	Several transitions of CN (cyanogen radical, including ^{15}N and ^{13}C isotopes)
183.310 GHz	H_2O (water vapor)
219.560, 220.399, and 230.538 GHz	CO (carbon monoxide, including ^{13}C and ^{18}O isotopes)
265.886 GHz	HCN (hydrogen cyanide)
267.557 GHz	HCO^+ (formylium)
271.981 GHz	HNC (hydrogen isocyanide)

TABLE 5 Priority 2 Spectral Lines

Spectral Line Frequencies	Atomic and Molecular Species
327.384 MHz	Deuterium [While this line has not yet been detected with confidence, it is known that deuterium is present in the interstellar medium. When the line is detected, it will certainly merit inclusion in the Priority 1 list.]
3263.794, 3335.481, and 3349.193 MHz	CH
14.488 GHz	H_2CO (formaldehyde)
22.834, 23.098, and 24.139 GHz	NH_3 (ammonia)
42.821, 43.122, and 43.424 GHz	SiO (silicon monoxide)
72.409 GHz	H_2CO (formaldehyde)
93.17 GHz	N_2H^+ (dinitrogen hydronium)
140.840, 145.603, and 150.498 GHz	H_2CO (formaldehyde)
144.8207 GHz	DCN (deuterated cyanide)
174.6-174.85 GHz	C_2H
177.2 GHz	HCN (hydrogen cyanide)
178.4 GHz	HCO^+ (formylium)
181.2 GHz	HNC (hydrogen isocyanide)
186.4 GHz	N_2H^+ (dinitrogen hydronium)
279.511 GHz	N_2H^+ (dinitrogen hydronium)

V. PASSIVE SERVICE ALLOCATIONS AND THEIR JUSTIFICATION

The following comments are ordered according to increasing frequency of the band concerned.

Comments

1. 13.36-13.41 MHz: This band was allocated to the Radio Astronomy Service by the World Administrative Radio Conference in 1979 (WARC-79). It has proved useful for a number of investigations that previously were impossible because of a lack of protection. The allocation is shared on a primary basis with the Fixed Service worldwide and on a primary exclusive basis in the United States.

2. 25.55-25.67 MHz: This band was allocated to the Radio Astronomy Service on a primary exclusive basis by WARC-79. This band is especially useful for observations of the sun and radio bursts from Jupiter (caused by interactions with its moon Io).

3. 37.50-38.25 MHz: This allocation was modified only slightly by WARC-79. On a worldwide basis the Radio Astronomy Service has a secondary allocation shared with the Fixed and Mobile Services. In the United States the band 38.00-38.25 MHz is shared on a primary basis with the Fixed and Mobile Services. Despite the secondary allocation, this band is often free of interference and is quite useful for radio astronomy. It should be broadened and changed to a primary, exclusive allocation worldwide.

4. 73.0-74.6 MHz: This primary exclusive allocation for the Radio Astronomy Service applies only in Region 2 (before WARC-79 it also applied in Region 3). Observations with the Arecibo 305-m radio telescope may be affected by active use of this band by the Fixed and Mobile Services in Cuba and other countries included in Footnote 570. A primary exclusive allocation on a worldwide basis is highly desirable; notification of use is required in Regions 1 and 3 (Footnote 568), and in Region 3 (with some exceptions) the band 79.75-80.25 MHz is allocated on a primary basis to the Radio Astronomy Service.

Justification (1, 2, 3, 4)

Most radio sources (such as radio galaxies, quasars, and supernova remnants) have characteristic nonthermal spectra produced by synchrotron emission from relativistic cosmic-ray electrons moving in galactic-scale magnetic fields. These nonthermal sources typically have radio spectra with negative slopes of ~0.8 in a graph of log (flux density) versus log (frequency). Hence such sources have higher radio flux densities at lower frequencies. The hundreds of pulsars in the Milky Way Galaxy (rotating neutron stars that act as giant particle accelerators) also have nonthermal radio spectra that have even more negative slopes and higher relative flux densities at low frequencies. However, at sufficiently low frequencies (10-100 MHz), the emission processes, conditions in the radio sources, or conditions in the surrounding environments cause the spectra of these radio sources to turn over or decrease with frequency (see Figure 1). Measuring the low-frequency spectra of such sources is essential for measuring and understanding their physical properties.

This low-frequency range also has a great importance in the observations of both the thermal and nonthermal diffuse radiation in our own Milky Way Galaxy. Such galactic observations give information on the high-energy cosmic ray particles in our galaxy and their distribution, and also on the hot ionized plasma and star birth in the disk of our spiral galaxy. In particular, the ionized interstellar clouds can be studied at low frequencies where their spectra approximate the Planck thermal radiation (blackbody) law. Several hundred such galactic clouds appear approximately as blackbodies at frequencies below ~100 MHz. Such spectral observations can be used directly to measure the physical parameters of the radiating clouds, particularly their temperatures.

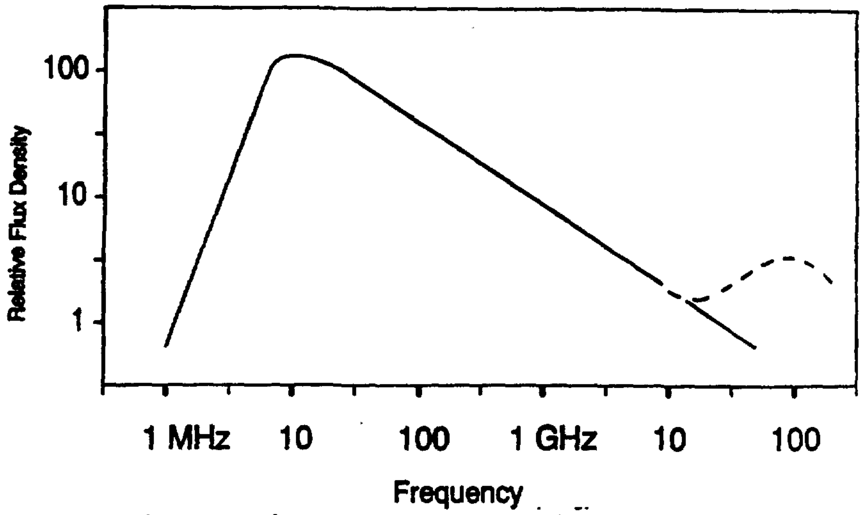

FIGURE 1 Spectrum of a typical nonthermal radio source. The dashed line shows the "compact" high-frequency component found in some sources.

Other important radio observations made at frequencies below ~100 MHz are those of solar bursts. Occasionally, and frequently during sunspot maximum, dramatic radio bursts of several different characteristic types are generated in the sun's atmosphere. Such bursts are sometimes associated with solar flares, which are sudden violent explosions in the sun's chromosphere. The radio bursts are observed from ~20 to ~400 MHz and are more intense at the lower frequencies. The high-energy particles ejected from the sun during these bursts interact with the earth's ionosphere and the stratosphere. Such interactions cause severe interruptions in radio communications and power systems, and can also have dangerous effects on aircraft flights above 15,000 meters. Studies of radio bursts aim to allow us to predict failures in radio communications and to forecast other effects. Knowledge of the high-energy particle ejections from the sun is essential for space exploration missions, both manned and unmanned. Continuous monitoring of the sun's activity will remain a high priority for the foreseeable future.

Also significant is the peculiar nonthermal burst-like radiation from the giant planet Jupiter, which is best observed at frequencies from ~15 to ~40 MHz. Extensive observations are being made at low frequencies in order to study this peculiar radiation. It was observed by the Voyager spacecraft, but further ground-based studies are essential.

These four allocations have proven to be invaluable for radio astronomy. They would be even more valuable if all four were allocated to the Radio Astronomy Service on a primary exclusive basis that extended to all three regions.

Comments

5. 150.05-153 MHz: This is a shared, primary allocation in Region 1. It falls near the middle of a wide gap in continuum coverage (see No. 3 in the "General Considerations" above). In the United States, a large amount of interference occurs in this band. A continuum band is badly needed between the current 74 and 408 MHz allocations, and it may be possible to have Regions 2 and 3 join Region 1. This band is widely used in the United Kingdom and is a major band for the Giant Meter-Wave Radio Telescope (GMRT) in India. Further worldwide consolidation would be most desirable.

6. 322-328.6 MHz: This important band gained additional status at WARC-79 and has become a widely used band throughout the world. It has now been implemented on the VLA and is widely used for VLBI experiments between countries (see No. 2 in the "General Considerations" above). It is not allocated to the passive services in the United States.

7. 406.1-410 MHz: This is an important continuum band where regional protection (U.S. 117) is often necessary. Additional allocation up to 414 MHz would be desirable.

8. 608-614 MHz: Extension of the primary allocation from Region 2 to Regions 1 and 3 would be desirable. A continuum band such as this one is needed between the 408 and 1400-1427 MHz bands. Better protection from adjacent channel interference is badly needed. The band is also used by the GMRT in India.

Justification (5, 6, 7, 8)

One of the most interesting and significant discoveries in radio astronomy has been the detection of pulsars. These objects are now understood to be highly condensed neutron stars that rotate with a period as short as a millisecond. Such objects are produced by the collapse of the cores of very old stars during the catastrophic explosions known as supernova outbursts. The radio spectra of pulsars indicate a nonthermal mechanism, perhaps of synchrotron emission type. Observations have shown that the pulsars are strongest at frequencies in the range from ~50 to 600 MHz; hence, most of the pulsar observations are being performed at such frequencies. With improved sensitivities at higher frequencies, these sources are now observed at up to several gigahertz.

The discovery and the study of pulsars during the last two decades have opened up a major new chapter in the physics of highly condensed matter. The study of neutron stars with densities of the order of 10^{14} g/cm^3 and with magnetic-field strengths of 10^{12} gauss has already contributed immensely to our understanding of the final state in stellar evolution and has brought us closer to understanding black holes (which are thought to be the most highly condensed objects in the universe). Observations of binary pulsars have verified the existence of gravitational radiation at the level predicted by the theory of relativity. Low frequency bands 6-8 are indeed important for pulsar observations. The need for exclusive bands at every octave is clearly indicated.

The frequency band 322-328.6 MHz has the desired octave-spacing relation with the 150.05-153 MHz and 608-614 MHz bands. Large radio telescopes in India, The Netherlands, and the United States at the Arecibo telescope in Puerto Rico, as well as the VLA and the Very Long Baseline Array (VLBA), operate in this band. High-resolution observations of radio galaxies and quasars have been made with the antenna in India using the method of lunar occultations. This method uses the moon's disk, which occults distant radio sources as its apparent position changes on the sky. From such occultations, or eclipses, it has been possible to determine the shapes and positions of many extragalactic radio sources with very high accuracies, of the order of 1 arc second.

The frequency range 322-328.6 MHz also contains the hyperfine-structure spectral line of deuterium at 327.4 MHz, the discovery of which astronomers consider highly significant. The abundance of deuterium relative to that of hydrogen is related to the problems of the origin of the universe and the synthesis of the elements. A determination of the deuterium abundance in the universe will certainly help in defining the most probable theory of the origin and evolution of the universe. Ultraviolet observations of deuterium show that its abundance in space is not constant, suggesting that studies of its abundance may be of increasing significance.

Many observatories, worldwide, have added 327-MHz receivers to their telescopes. This has become a major new frequency for VLBI observations between continents. The Westerbork Synthesis Radio Telescope in The Netherlands and the VLA in the United States have been equipped for operation in this band. Japanese radio astronomers have constructed a three-station array for observations of interplanetary scintillation near 327 MHz. In the United States, the band is being used at Owens Valley and Hat Creek for deuterium searches. U.S. radio astronomers certainly support efforts to protect this band. The band is also used by the GMRT in India.

Comments

9. 1330-1400 MHz: This band is important for observations of red-shifted neutral hydrogen gas from external galaxies and has footnote protection. The lower-frequency limit for footnote 718 should be decreased to approximately 1250 MHz. Successful observations of red-shifted neutral atomic hydrogen have already been made in a quasi-continuous range of frequencies down to 1260 MHz. Below this frequency, such detections have been made only at individual, isolated frequencies.

10. 1400-1427 MHz: This is the most important band for hydrogen-line observations and is also important for continuum observations. Extending the worldwide exclusive allocation downward in frequency to 1330 MHz would greatly benefit radio astronomy by allowing observations of distant, red-shifted hydrogen clouds. The extension of the allocated 1400-1427 MHz band to 1330-1427 MHz would also benefit passive remote sensing of the earth's soil moisture.

Justification (9, 10)

One of the most important spectral lines at radio wavelengths is the 21-centimeter line (1420.406 MHz) of neutral atomic hydrogen. Since its discovery in 1951, radio observations of this line have been used to study the structure of our galaxy and other galaxies. Because of Doppler and cosmological shifts due to the distance and motion of the hydrogen clouds that emit this radiation, the frequency for observing this line emission ranges from ~1330 to ~1430 MHz. Numerous and detailed studies of the neutral hydrogen distribution in our galaxy and in other galaxies are being made. Such studies are being used to investigate the state of cold interstellar matter, the dynamics, kinematics, and distribution of the gas, the rotation of our galaxy and other galaxies, and the masses of other galaxies.

The 21-centimeter neutral hydrogen emission is relatively strong, and with current receiver sensitivity such emission is detectable from any direction in our galaxy and from a very large percentage of the nearby galaxies.

In recent years, the physics of the ionized hot gaseous clouds between the stars has been studied by observations of radio lines of excited hydrogen, helium, and carbon. Some of these studies have been made at frequencies of 1399 and 1424 MHz. Detailed observations of radio recombination lines in many interstellar clouds have made possible the derivation of physical parameters such as temperature, density, and velocity distributions. Radio studies have been particularly helpful for observations of these clouds, which are partially or totally obscured at optical wavelengths by interstellar dust.

Comments

11. 1610.6-1613.8 MHz: The 1612-MHz transition is an extremely important satellite line of OH. This line emission occurs in many types of objects in the galaxy, and high-angular-resolution observations of these objects in this line measure their distances and can be used collectively to measure the distance to the center of the galaxy. The secondary allocation should be considerably strengthened or a narrow, worldwide allocation made. See Comment 12.

12. 1660-1670 MHz: To afford the level of protection needed in order to observe the primary OH lines properly, CORF urges exclusive allocation for radio astronomy in this band. These lines are of extreme importance to radio astronomy.

13. 1718.8-1722.2 MHz: See Comment 11, which applies here also.

Justification (11, 12, 13)

A relatively new and very exciting branch of astronomy is astrochemistry. This subject involves the study of the formation of molecules in space and their abundance. In 1963, OH, the hydroxyl radical, was the first molecule to be detected at radio frequencies. Today, radio astronomers have detected about 80 different organic and inorganic molecules in space. Space chemistry is vital in understanding the physics of stars and planets. The OH molecule has been observed widely in our galaxy in its ground-state transitions at 1665 and 1667 MHz and its satellite lines at 1612 and 1720 MHz. OH has been detected in thermal emission and absorption in several hundred different molecular complexes in our galaxy. Besides the thermal emission, extremely narrow and intense emission lines have been seen in certain galactic regions. This emission is due to maser action and can be associated with star-forming regions and with more evolved stars.

The study of OH and other characteristic molecules is thus of great interest for investigating the physical phenomena associated with the formation of protostars and the initial stages of star formation. Observations of OH maser sources using the powerful technique of very-long-baseline interferometry (VLBI) have shown that the masing regions have apparent angular sizes on the order of 0.01 arc second or less. Such apparent sizes translate to linear sizes of the order of a few times the mean distance between the earth and the sun (150 million kilometers) and occur at the heart of regions with active star formation. The technique of VLBI makes use of two or more widely separated radio telescopes (tens to several thousands of kilometers apart), and simultaneous observations are made with time synchronization provided by atomic clocks. The data are recorded on magnetic tape at each telescope or are communi-cated via satellite and recorded elsewhere. At a later time the data from the different stations are correlated using the accurate time signals recorded with the data. The angular resolution achieved with such techniques depends not on the size of the individual telescopes but on the distance between them. VLBI observations have a great impact on the study of molecular emission regions in space, the nuclei of galaxies, and even of terrestrial processes, such as plate tectonic movement. The United States is building a dedicated system of ten VLBI telescopes from Hawaii across the continent to the Virgin Islands called the VLBA, or Very Long Baseline Array, which will achieve unprecedented resolution.

Hydroxyl (OH) and other molecules are being used to study the spatial distribution of the molecular component in our galaxy and other galaxies. OH can be seen in other galaxies by absorption against radio sources in galactic nuclei and by maser emission. The OH megamaser emission from galactic nuclei can be more than a million times more luminous than galactic masers and can be seen to great distances. The present redshift limit for extragalactic masers is 50,000 km/s ($z = 0.17$), which causes the OH line to be observed at 1428 MHz. These powerful megamasers are due to maser action within the cores of galaxies; this action results in amplification (rather than absorption) of the nuclear radio continuum. Use of the OH line to study these very peculiar and active galaxies allows radio astronomers to diagnose the temperature and density of the molecular gas in the center of these galaxies.

Emission lines from ^{18}OH and ^{17}OH have been detected in some molecular regions of our galaxy. The data from these lines allow the study of the abundances of the oxygen isotopes involved. Such studies are a crucial part of understanding the network of chemical reactions involved in the formation of atoms and molecules. The data can help astronomers to understand the physics of stellar interiors, the chemistry of the interstellar medium, and the physics of the early universe.

Comments

14. 2200-2290 MHz: This band is widely used in conjunction with the Space Research band just above it. This usage allows radio scientists to use space tracking equipment to support astronomical observations and radio telescopes to support important space missions. In particular, major geodetic and astrometric programs are being carried out jointly in the frequency range 2200-2300 MHz.

15. 2290-2300 MHz: This band, allocated to Space Research (Deep Space and Space-to-Earth), can also be used for VLBI observations in radio astronomy. A secondary shared status should be sought in this band.

16. 2655-2690 MHz: This is an important extension of a useful, but too narrow, continuum band at 2690-2700 MHz. The broadcast satellite service, at present allocated as one of the users of the band at 2655-2690 MHz, interferes with radio astronomy when it broadcasts from space to the earth in channels adjacent to the radio-astronomy band. A domestic agreement has been made for the satellite service to be implemented starting from the bottom of the band at 2500 MHz and then proceeding to higher frequencies. This should leave the 2670-2690 MHz band free of interference for some years.

17. 2690-2700 MHz: This band, while useful and fulfilling the octave-need requirement, is narrow relative to most of the continuum bands currently allocated to the Radio Astronomy Service. If possible, the width of the band should be increased. In passive sensing, it is used for measurement of soil moisture and sea surface temperature.

Justification (14, 15, 16, 17)

The study of the continuum emission of radio sources requires observations throughout a very wide frequency range. The spectral regions at 2200 to 2300 MHz and 2655 to 2700 MHz are excellent bands for continuum measurements partly because the galactic background radiation is low. Observations of thermal and nonthermal radio sources at these frequencies help to define the shape of their spectra, which in turn can give information on the physical parameters of the radiating sources such as densities, temperatures, and magnetic fields. The knowledge of these physical parameters is essential to explain the physical processes that operate in radio sources to produce radio radiation. Many extragalactic radio sources show a "break" in their nonthermal spectrum in the region between 1 to 3 GHz, and continuum measurements in the range of 2 to 3 GHz are essential to define such a spectral characteristic accurately. The spectral "break" at relatively high frequencies from synchrotron sources is closely related to the lifetime of relativistic particles in radio galaxies and quasars. Such information is crucial to our understanding of the physical processes taking place in radio sources.

These frequency bands are also useful for galactic studies of ionized hydrogen clouds and the general diffuse radiation of the galaxy. Since, at such frequencies, available radio telescopes have adequate angular resolution (narrow beams, of the order of 10 arc minutes for large telescopes), many useful surveys of the galactic plane have been performed, including the regions of the galactic center, which is invisible at optical wavelengths because of the interstellar absorption by dust particles. The center of our galaxy is perhaps its most interesting region, and it can only be observed at infrared and radio wavelengths, since such long wavelengths are not affected by the dust particles in interstellar space. The study of the nuclei of galaxies, including the nucleus of our own galaxy, is emerging as an extremely important and fundamental topic in astronomy. Problems that can be studied in these objects include the state of matter and the possibility of the existence of black holes in galactic nuclei; the explosive activities and the production of intense double radio sources from galactic nuclei; the influence of galactic nuclei on the morphological structure of galaxies; the formation of galaxies and quasars; and many other relevant and major astro-physical topics.

An important study at radio wavelengths is the polarization of the radiation that is observed from radio sources. Radio sources are often found to be weakly linearly polarized, with a polarization angle that depends on frequency. This effect is due to the fact that the propagation medium in which the radio waves travel to reach us is composed of charged particles, electrons, and protons, in the presence of magnetic fields. The determination of the degree and angle of polarization gives us information on the magnetic fields and electron densities of the interstellar medium and in certain cases on the nature of the emitting sources themselves. The degree of polarization of radio waves is higher at higher frequencies. The frequency bands near 2300, 2700, and 5000 MHz are important bands for polarization measurements.

Comments

18. 4825-4835 MHz: The formaldehyde (H_2CO) line is one of the four or five most important spectral lines in radio astronomy. CORF urges that the current footnote be upgraded to a narrow, exclusive, worldwide allocation. See Comments 19 and 20 below.

19. 4800-4990 MHz: This is an important extension of a heavily used, but too narrow, continuum band at 4990-5000 MHz. CORF supports its allocation to radio astronomy on a shared basis with fixed and mobile services, which has been implemented in all three regions but not in the United States.

20. 4990-5000 MHz: This band, while useful in fulfilling the octave-need requirement, is narrow relative to most of the continuum bands currently allocated to the Radio Astronomy Service and is also useful for passive remote sensing of the earth. If possible, the width of the band should be at least doubled. If this band could be widened to include the H_2CO line (see Comment 19) or widened and moved to include the 4830-MHz H_2CO line, not only would the H_2CO be afforded exclusive, worldwide protection, but the radio-astronomy continuum band could also be placed to avoid interference from the Microwave Landing System above 5000 MHz. In either case, a 1- to 2-percent bandwidth is most desirable. This band is also important for passive sensing of the earth.

Justification (18, 19, 20)

Formaldehyde (H_2CO) is detected in interstellar clouds at 4829.66 MHz. The H_2CO line at this frequency is considered to be one of the most important radio lines in the entire spectrum, primarily because it can be detected in absorption in almost any direction where there is a continuum radio source. The distribution of H_2CO clouds can give independent evidence of the distribution of the interstellar material and can help in understanding the structure of our galaxy. H_2CO lines from the carbon-13 isotope and oxygen-18 isotope have been detected, and studies of the isotopic abundances of these elements are being carried out.

The combination of the 4830-MHz and 14.5-GHz formaldehyde lines is a sensitive and useful diagnostic of the density in the emitting gas. Extragalactic formaldehyde megamaser emission and absorption are found in a growing number of galaxies. Since formaldehyde is a good tracer of intermediate- to high-density gas, this line is very important for the study of the molecular structure of other galaxies.

The spectral band around 5 GHz has been one of the most widely used frequency ranges in radio astronomy during the last decade. Astronomers have made use of this frequency range in order to study the detailed brightness distributions of both galactic and extragalactic objects. Detailed radio maps of interstellar ionized hydrogen clouds and supernova remnants have assisted our understanding of the nature of such celestial objects. These radio maps define the extent and detailed morphology of radio sources and enable us to make conclusions concerning their structures and dynamics and to derive physical parameters of the sources such as their total masses.

Heavy use has been made of the radio astronomy band at 5 GHz for VLBI observations. Angular resolutions of 0.0003 arc seconds have been achieved with intercontinental baselines, and many countries (Australia, Canada, Great Britain, The Netherlands, South Africa, Spain, Sweden, U.S.S.R., and Germany) have collaborated in this effort. From such studies, astronomers are finding that quasars are composed of intricate structures with many strong localized sources of radio emission.

The technique of VLBI has many other practical applications, such as studies of continental drift, the rotation rate of the earth, polar wandering, latitude determination, spacecraft navigation, and earthquake studies. Such experiments are able to determine intercontinental distances with accuracies of a few centimeters.

International VLBI observations make heavy use of almost all of the radio astronomy bands. At the higher frequencies, the angular resolution is even better than at 5 GHz, and increased emphasis on the bands near 15 GHz and 22 GHz is expected.

Comments

21. 8400-8500 MHz: This band is widely used for studies in conjunction with, and in support of, geodetics and Space Research (space to earth) experiments. Common use of this band for radio astronomy observations using VLBI and for space science allows the full and effective use of costly facilities built for space research and communications and for radio astronomy. This band should be allocated to the Radio Astronomy Service on a secondary shared basis.

22. 10.60-10.70 GHz: The committee urges worldwide, exclusive passive allocation for this continuum band. The worldwide, exclusive allocation of the 10.6-10.7 GHz band to passive services also would benefit global passive remote sensing of precipitation. Many rainfall estimation techniques currently require the use of this frequency band.

23. 14.47-14.50 GHz: This band is important for study of one of the formaldehyde (H_2CO) lines and, in conjunction with the 4.83 GHz formaldehyde line, is a sensitive diagnostic for the density of the emitting regions (see Comments 18 above and 24 below).

24. 15.35-15.40 GHz: While no change in status is needed in this worldwide exclusive allocation, it is noted that it would be somewhat more desirable to substitute in place of this band a 1- to 2-percent continuum band roughly centered on the formaldehyde line at 14.4885 GHz. This new band would still be centered between the 10.6- and 23.8-GHz continuum bands while affording excellent protection for the 14.4885-GHz line.

25. 18.6-18.8 GHz: This transmission window is used for rainfall measurement by passive earth exploration satellites. Primary allocation in Region 2 should be extended to all three regions.

Justification (21, 22, 23, 24, 25)

The band at 10- to 15-GHz provides some of the best angular resolutions (~2 arc minutes) using many large and accurate radio telescopes. Many of the nonthermal synchrotron sources are just detectable at higher frequencies, and this frequency range gives us observational information at the highest frequency where such sources can be detected reliably. This high-frequency range is also extremely important for monitoring the intensity variability of the quasars. These objects, which could be the most distant celestial objects that astronomers can detect, and which produce surprisingly large amounts of energy, have been found to vary in intensity with periods of weeks and months. Such observations lead us to estimate the sizes of these sources, which turn out to be very small for the amount of energy they produce. The variability of quasars (and some peculiar galaxies) is more pronounced at higher frequencies, and observations at these frequencies facilitate the discovery and the monitoring of these events. The energy emitted during any one such burst from a quasar is equivalent to the complete destruction of a few hundred million stars in a period of a few weeks or months. Astronomers do not yet understand the fundamental physics that can produce such events. Observations of the size and variability of these sources are the primary means that can be used to determine their nature. These observations are now best performed in the frequency range 10 to 15 GHz.

The small sizes of the quasars are revealed from the VLBI observations mentioned above. Such observations are also being made in the frequency band at 10.6- to 10.7-GHz, and observations at 15.40 GHz have been successful. The higher frequencies provide us with better angular resolutions and enable us to determine more accurately the sizes and structures of quasars.

The important formaldehyde (H_2CO) line at 14.4885 MHz has been observed in the direction of many galactic sources. Since this line originates from the upper levels of ortho-formaldehyde, its study gives valuable information on the physical conditions of the interstellar medium because the excitation energy required to produce this line is different from the energy required to produce the H_2CO line observed at 4829.66 MHz.

Comments

26. 22.21-22.50 GHz: The H_2O line at 22.235 GHz is of such importance to the Radio Astronomy and the Earth Exploration Satellite Services that it merits a worldwide, exclusive, narrow-band allocation. The 22.235-GHz transition of water vapor has been detected as maser emission from galactic nuclei and may therefore be detectable at great distances. Observations of such emission may provide a direct means of measuring the distances to very distant galaxies.

27. 23.6-24.0 GHz: This is an important continuum band that also covers the three major ammonia (NH_3) lines.

Justification (26, 27)

The two narrow bands, 22.21-22.50 GHz and 23.6-24.0 GHz, are important primarily because they include the H_2O and NH_3 molecular lines, respectively, which have been detected in the interstellar medium both in our galaxy and other galaxies.

The discovery in 1968 of the H_2O molecule in interstellar space presented many new and interesting puzzles. These lines are extremely intense and variable; consequently they are occasionally the most intense radio sources in the sky (at 22.2 GHz) other than the sun and the moon. It was soon discovered that the intensities of these lines are highly variable, that the sizes of the H_2O sources are extremely small (a few astronomical units), and that the lines are highly polarized. Interstellar H_2O maser action is necessary to explain such observations. Such sources seem to be similar to the OH sources discussed above. With high-frequency (hence high-velocity) resolution, H_2O sources have been observed to show multiple components, each one with a slightly different velocity in the line of sight. Astronomers believe that such molecular clouds are related to the formation of protostars. VLBI observations at 22.2 GHz provide valuable information on the sizes and structure of the H_2O maser sources.

The discovery of NH_3 (ammonia) in interstellar space presented an example of a molecule radiating thermally. Maser action is not necessary to explain the NH_3 observations. The distribution of NH_3 clouds in the galaxy and their relation to the other molecules that have been discovered is of great interest. The analysis of the NH_3 line observations enables us to deduce accurately the temperature of the interstellar medium where these clouds exist. They also assist us (indirectly) in deducing the concentration and abundance of molecular hydrogen (H_2), which cannot be observed at radio wavelengths since it produces no radio lines.

Comments

28. 31.3-31.8 GHz: The basic present allocation (31.3-31.8 GHz) is nearly the desired 2-percent bandwidth. This band is also used for passive remote sensing of terrestrial cloud water and precipitation.

29. 36-37 GHz: This transmission window is useful for passive remote sensing of terrestrial cloud water and precipitation, primarily as an alternative to 31.3-31.8 GHz.

Justification (28, 29)

The frequency region from 31.2 to 37.5 GHz is the first atmospheric window in the millimeter radio region where ground-based observations can be made. On either side of this frequency band, water and oxygen molecules in the earth's atmosphere attenuate the incoming radiation, although only the O_2 absorption beginning about 50 GHz is sufficiently strong to render observations impossible. This spectral region contains lines of CH_3N, a molecule that is becoming of increasing importance as more long-chain molecules of the form HC_xN ($x = 1, 3, 5, 7, 9 \ldots$) are found. The region has also been useful in defining the high-frequency continuum spectra of galactic and extragalactic objects. It is anticipated that the use of this band will be greatly increased as large telescopes become operational at these frequencies. For instance, the new 100-meter Green Bank Telescope (GBT) is expected to operate at frequencies as high as that of this band.

Comments

30. 42.5-43.5 GHz: This band encompasses the vibrational transitions of SiO. All of these transitions have been detected as maser emission from the regions of late-type stars.

31. 48.94-49.04 GHz: This band contains the lines of CS and its isotopes. They have been detected in molecular clouds. Since CS is a good high-density tracer, whereas CO is a low-density tracer, CS is extremely important as a diagnostic for the molecular material in other galaxies and in particular the active nuclei and starburst galaxies.

32. 50.2-50.4 and 51.4-59.0 GHz: Passive remote sensing instruments measure the earth's atmospheric temperature profiles using oxygen transitions within these bands.

33. 60-61.5 GHz: This band has potential uses in passive remote sensing of mesospheric temperature profiles.

34. 64-66 GHz: This band is used for passive remote sensing of the atmosphere of the earth from space. In particular, it is valuable for measuring atmospheric temperature profiles using oxygen transition lines within these bands.

Justification (30, 31, 32, 33, 34)

The allocated band at 42.5- to 43.5-GHz provides protection for observations of the SiO molecule. The lines of SiO indicate maser emission, the mechanism of which is not understood but extends over a wide range of excitation in the SiO molecule.

The lines of CS and its less common isotopes, $C^{33}S$, $C^{34}S$, and ^{13}CS, have been shown to be constituents of both giant molecular clouds and cool dark clouds. Since the $J = 1 \rightarrow 0$ transition arises in the lowest possible energy levels of CS, this molecule will become increasingly important in probing cool clouds. Other molecules with detected transitions in this frequency range include H_2CO, CH_3OH, and OCS.

Comments

35. 86-92 GHz: This is a wide and useful band near an atmospheric absorption minimum. At least 72 spectral lines fall in this band and are thus already protected through this allocation. This atmospheric transmission

window is also useful for remote sensing of terrestrial clouds and precipitation, and provides one of the most useful microwave channels for this purpose.

36. 100-102 GHz: This band is useful for passive remote sensing of the earth and radio astronomy observations of red-shifted CO in distant galaxies.

Justification (35, 36)

Since there is relatively little absorption from atmospheric O_2 and H_2O, the millimeter band between 86 and 92 GHz is perhaps the best high-frequency region for both continuum and line observations of celestial objects. Over 20 molecules have been detected in this frequency range, as have 25 different isotopic species. These include such simple molecules as SO, SO_2, SiO, SiS, HCN, HCO, CHO^+, and HC_2 and such complex molecules as CH_3CH_2OH, CH_3CH_2CN, and CH_3OCH_3. Two vibrational states of the transitions of SiO fall in this range; SiO is one of the few molecules showing maser emission and the only one showing strong maser emission in an excited vibrational state. HCN, HCO, and HCO^+ are vitally necessary participants in the ion-molecule reactions believed to be key in the formation of many other molecules in the interstellar gas. Furthermore, some molecules have several isotopic species in this range so that isotopic abundance ratios and optical depth effects can be studied. As an example, the basic molecule HCN has the isotopic species $H^{12}C^{14}N$, $H^{13}C^{14}N$, and $H^{12}C^{15}N$ in the 86-92 GHz range, and all have been observed in the interstellar gas. It is clear that this region of the millimeter spectrum will remain one of the most used for radio astronomy.

Comments

37. 105-116 GHz: Carbon monoxide (CO) is among the most important of the interstellar molecules. The primary line is at 115.271 GHz, and important isotopic variations of the molecule have lines at somewhat lower frequencies; for example, $^{13}C^{16}O$ has its line at 110.2 GHz. Furthermore, the important diatomic molecules CN and CS and isotopic variations of these molecules fall in the same general region of the spectrum. The upper portion of this band is needed for passive remote sensing of atmospheric temperature profiles.

38. 116-126 GHz: Passive remote-sensing instruments measure the earth's atmospheric temperature profiles using the oxygen transition at the center of this band at 118.75 GHz. Additional protection is desirable.

Justification (37, 38)

The discovery of interstellar CO at 115.271 GHz has been of fundamental significance for the subject of astrochemistry. This is primarily because CO is a relatively stable molecule compared with other molecules discovered in the interstellar medium, and also because CO seems to be very abundant and exists almost everywhere in the plane of our galaxy as well as in a number of other galaxies. Studies have yielded new information on the distribution of gas in spiral galaxies. Allowance for Doppler shifts characteristic of nearby and even distant galaxies is essential for adequate protection of radio spectral lines.

Because the CO molecule is so ubiquitous, and therefore present under nearly all physical and chemical conditions, its emission is the principal tool available to astronomers today for the study of the star forming gas in the Milky Way Galaxy, and even in quite distant galaxies. CO studies tell us about disks around forming stars and, in the future, with the expansion of millimeter-wave interferometer instruments, they may tell us about the conditions for planet formation. Furthermore, CO emission studies reveal the presence of bursts of star formation activity in nearby and, in some cases, distant galaxies. These bursts have recently been related to collisions between galaxies and possibly to the formation of massive black holes and quasars.

The isotopically substituted species $^{13}C^{16}O$, $^{12}C^{18}O$ have also been detected in many regions in the galaxy. They tell us about the ratios of the isotopic abundances of the stable forms of carbon and oxygen and therefore test theories of nucleosynthesis in stellar burning and models of star formation rates for molecular clouds within our Galaxy.

Comments

39. 164-168 GHz: This transmission window is important for passive remote sensing of terrestrial water vapor.

40. 182-185 GHz: This band, shared with passive space research, is important for remote sensing studies of water vapor.

Justification (39, 40)

Allocations at 164-168 GHz and 182-185 GHz are important for radio astronomy and other passive services. Water, an important constituent of interstellar clouds as well as of the terrestrial atmosphere, has only two low-lying radio-frequency lines, 22.235 GHz and 183.310 GHz. Both of these water lines are used for radio astronomy and passive sensing. Like the 22 GHz-line, the 183-GHz line is produced by maser activity in the interstellar medium and is observed near hot young stars. However, the line is strongly attenuated by the earth's atmosphere, and so the observations are easily susceptible to interference.

Comments

41. 217-231 GHz: This is an important primary allocation, shared with space research (passive). This band contains the second available rotational line of carbon monoxide ($^{12}C^{16}O$), together with its isotopic variants $^{13}C^{16}O$ and $^{12}C^{18}O$. These are very strong and important lines both within our galaxy and in distant galaxies. In combination with the first lines in the 106-116 GHz band, they permit the determination of the physical characteristics of the gas within the galaxies. The coverage for $^{12}C^{16}O$ extends to galaxies at velocities of 2000 km/s, but should be much greater to give protection to future work to learn about the structure and evolution of much more distant galaxies.

Besides CO lines, there are many lines of complex molecules observable in this band and neighboring bands. Each complex molecule may have many lines spread throughout the radio spectrum, so it is not practical to request protection for the various individual frequencies. Rather, in analogy with the protection given for continuum studies, the requirement is for a number of relatively wide, well-protected bands, placed at strategic intervals throughout the spectrum.

Justification (41)

The frequency band at 217-231 GHz is in the center of the highest spectral region at millimeter wavelengths where there is a useful atmospheric window. On each side of the 200-300 GHz region, atmospheric H_2O absorption makes ground-based observations difficult or impossible.

Radio astronomy is extremely active in this region of the spectrum because of the unique insights spectroscopic studies provide into star formation, interstellar chemistry, the late stages of stellar evolution, and the chemical composition of the Milky Way and other galaxies. The most important line in this band is that of carbon monoxide, which is essential to observe over as wide a spectral range as possible in order to study the kinematics and evolution of distant galaxies. In addition to carbon monoxide, a large number of lines belonging to many interstellar species have recently been detected in this band and in neighboring regions of the spectrum. In the range from 208 to 260 GHz, about 1000 lines are now known. Several new telescopes are being constructed or have recently been completed to work in the range from 100 to 300 GHz and above, in the United States, Europe, and Chile. This spectral region is one of rapidly increasing activity in radio astronomy.

This band also provides a continuum window near the peak of the 2.7 K cosmic background radiation. This radiation, emitted when the universe was only about 100,000 years old, is one of the most significant discoveries in the study of cosmology. Further detailed studies of its properties will yield unique information about the early universe. Observations of the cosmic background from the ground are severely limited by the high, variable intensity of atmospheric emission. Observations near this frequency are important for such fundamental measurement as the velocity of the galaxy with respect to the background radiation field and the rotation and symmetry of the universe. Because of the low intensity of the background radiation, accurate measurement of its distribution must be made from high-altitude aircraft, balloons, and spacecraft in an environment free from interference.

VI. THE PROTECTION OF RADIO ASTRONOMY OBSERVATIONS IN THE SHIELDED ZONE OF THE MOON

Future radio astronomy observations made from telescopes in the shielded zone of the moon will need to be protected. The reasons for this are discussed in CCIR Recommendation 479-1, "Protection of Frequencies for Radioastronomical Measurements in the Shielded Zone of the Moon" (see Appendix). The Committee on Radio Frequencies has been concerned for a number of years with protecting radio astronomy observations in this zone.

Along with discussions of establishing a lunar observatory in the next century (see, for example, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991), it is prudent for scientists to prepare for actions that may be needed to protect passive observations. The concept of a Lunar Quiet Zone has been studied and advanced as a valuable international resource for radio astronomers and for other scientists who conduct passive observations of the universe.

APPENDIX

Protection of Frequencies for Radioastronomical Measurements in the Shielded Zone of the Moon

CCIR Recommendation 479-1 (International Telecommunication Union, Geneva)

"The CCIR,

CONSIDERING

"(a) that some radioastronomical and other scientific experiments are difficult, and in certain cases impossible, to carry out on the surface of the Earth because of tropospheric and ionospheric absorption, scintillation, and radio interference;

"(b) that radioastronomical discoveries resulting from limited observations from spacecraft above the atmosphere of the Earth reveal unexpected new astronomical phenomena;

"(c) that further developments will enable experiments to be carried out in the relatively quiet environment in the shielded zone of the Moon;

"(d) that, in addition to the establishment of line-of-sight communication links for scientific and other purposes between the Earth and spacecraft, it may be necessary to establish links between stations on the far side of the Moon and other stations on or visible from the Earth;

"(e) that the shielded zone of the Moon is free from terrestrial radiation at all radio frequencies;

"(f) that Recommendation No. Spa 2-8 of the Radio Regulations expresses the desirability of maintaining the shielded area of the Moon as an area of maximum value for observations by the Radioastronomy Service and by passive space research and consequently as free as possible from transmissions;

"(g) that the same Recommendation also invited the CCIR to study the frequency bands most suitable for radioastronomy observations on the shielded area of the Moon and work out Recommendations concerning these bands as well as criteria for their application and protection;

"(h) that Earth satellites with high apogees, deep-space probes and transmitters located on the Moon may each illuminate the shielded zone;

"(i) that Report 539-1 contains preliminary guidelines on the use of the frequency spectrum in the shielded zone of the Moon,

"UNANIMOUSLY RECOMMENDS

"1. that in planning the use of the radio spectrum, both nationally and internationally, account be taken of the need to provide for radioastronomy observations in the shielded zone of the Moon;

"2. that, in taking account of such a need, special attention should be given to those frequency bands in which observations are difficult or impossible from the surface of the Earth;

"3. that the frequency spectrum should be used in the shielded zone of the Moon in keeping with the preliminary guidelines contained in Report 539-1.

"4. that in the frequency bands which would be considered for joint use by active and passive space stations in the shielded zone of the Moon, radioastronomy observations should be protected from harmful interference. To this end appropriate discussions between concerned administrations may be conducted."